A brief history of the development of radar in Great Britain up to 1945

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Radar was developed more or less simultaneously in several countries including Great Britain, the USA, Germany, Japan, France, Italy, Holland and the Soviet Union, in mutual isolation and in great secrecy during the middle to late 1930s.

The position in Great Britain was unique in that radar was developed to meet a clearly stated and most urgent military operational need (national air defence). The number of separate British radar developments during the period up to 1945 was very large, so that it is only possible in a paper of this length to summarise those of especial importance.

Following the First World War, Britain had reduced its armed forces including its air force to low levels of capability since the perception was that a further major war was very unlikely. The economic depression of the late 1920s and early 1930s, together with the strongly pacifist public sentiment, resulted in a relatively low public expenditure in armaments.

In the mid-1930s in Great Britain, the perception was that there was no practical defence against aerial bombing raids from Europe, the British Prime Minister of the time (Stanley Baldwin) stating in Parliament that 'the bomber will always get through'. A particular difficulty was that, in the absence of an effective air defence early warning system, it would be necessary to have formations of fighter aircraft (standing patrols) constantly patrolling the British coastal zones into which enemy bomber aircraft from Europe would be likely to intrude.

It was realised that with the fighter aircraft resources likely to be available to the RAF, the use of standing patrols would be impracticable, so a means of early warning of the approach of enemy aircraft towards the British Coast was essential.

By 1935, the rise of an aggressive military regime in Germany, together with statements made by German Luftwaffe officers to their British counterparts to the effect that Germany had embarked upon a very large scale military aircraft construction programme, led to informed circles in government and in the armed forces forming the view that war with Germany within the foreseeable future was becoming unavoidable.

At first, experiments with the use of sound location were carried out, with large parabolic mirrors constructed of concrete being built along the South Coast of England (some of which survive and can still be seen). However, by the time that these sound locators were installed, it was apparent that, due to the increasing speed of the modern bomber aircraft being built by Germany, sound location would give insufficient warning time to enable fighters to become airborne and to reach sufficient altitude to be successfully vectored to intercept approaching enemy bomber formations before they crossed the British coast.

At this time there was much scientifically uninformed speculation as to the practicability of shooting down aircraft and of incapacitating their crews by means of electromagnetic radiation (the so-called 'Death Ray'). As Superintendent of the British National Physical Laboratory, Robert Watson Watt was asked to advise the British Air Defence Committee as to whether such a weapon was feasible. By means of a few rapid calculations carried out by Watson Watt with the help of his assistant Arnold Wilkins, he was able to show that with the then current state of the art in high-frequency radio engineering, the required levels of concentrated radio-frequency power at the likely altitudes of attacking aircraft was impractical.

However, in common with similar workers in radio-frequency engineering in other countries, Watson Watt was aware that radio interference due to reflection of radio waves had been observed, and calculated that such an effect could be used to detect approaching aircraft, to enable fighters to become airborne and to successfully direct them by radio from the ground to intercept attacking bomber aircraft.

He received immediate financial backing from the British Government to carry out an experiment to determine whether such a means of aircraft detection would work in practice. In 1935, Watson Watt placed a radio receiver in a motor vehicle tuned to the BBC HF radio transmissions from its Daventry transmitter. As the aircraft passed between the transmitter and receiver, large fluctuations in the strength of the signal received were observed, which were clearly the result of reflections of the Daventry transmissions from the aircraft structure.

The experiments were observed by representatives of the British Government, with the result that Watson Watt was funded to develop a practical scheme of radar early warning for British Air Defence. By the outbreak of war with Germany in 1939, a chain of radar stations, known as 'Chain Home', had been built and commissioned covering the aerial approaches to England from Continental Europe (*Figure 1*).

In fact, in early 1939, General Martini, responsible for signals in the German Luftwaffe, arranged for an airship fitted with radio search receivers to patrol along the British

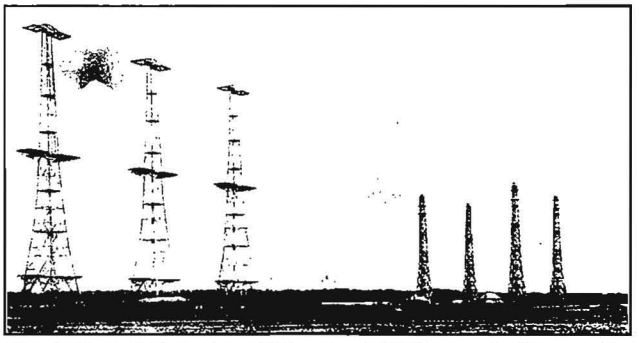

Fig. 1: Typical East Coast CH station (GEC Journal of Research).

coast in order to monitor British military radio transmissions and particularly to determine whether Britain had developed air defence radar. Although the airship was continuously tracked by the British Chain Home radar network, its transmissions were not recognised by the German airship, possibly because the radar transmissions were synchronised with the 50Hz frequency of the British National Electrical Power Distribution Grid and were mistaken for electrical interference.

A deficiency of Chain Home radar was its inability to detect low-flying aircraft due to its relatively low operating frequencies in the range of 20MHz to 55MHz with correspondingly coarse vertical antenna lobing structure, the bottom cut-off of the vertical pattern being at 2 degrees. In order to enable low-flying aircraft to be detected, the Chain Home Low (CHL) radar was developed which operated at approximately 200MHz with correspondingly finer vertical antenna lobing structure with a lower antenna pattern bottom cut-off.

The need to guide fighters to the immediate vicinity of enemy aircraft, especially at night, led to the development of Ground Controlled Interception (GCI) and Fighter Direction Radars, initially at operating at 200MHz, then at 50cm and latterly at 10cm. In 1935, Sir Henry Tizzard had correctly foreseen that a German daylight bombing offensive against Southern England would result in heavy losses for the attacker with the result that the Luftwaffe would turn to night bombing, to counter which British fighter aircraft would have to be fitted with Air Interception (AI) radar.

It was realised that for the antenna to be acceptably small for use on fighter aircraft, as short a wavelength as possible would have to be used. The highest frequency at which adequate transmitter power could be obtained was in the region of 200MHz and the first AI radars were developed at this frequency.

An especial limitation of airborne radars operating at 200MHz with antennas of small vertical aperture was that a strong return from the ground was obtained which prevented airborne targets being detected at a range greater than the fighter's height above the ground. To overcome this problem a system of Ground Controlled Interception (GCI) was developed in which special ground radars, having plan position indicator displays and able to determine aircraft height, were used, the ground radar controller vectoring the fighter aircraft by means of VHF radio until it was within close enough range of the bomber target aircraft to complete the interception using its own airborne AI radar.

Although the British work on radar development was in the context of Air Defence, applications to Anti-Aircraft Gun Laying were also foreseen and radars for these purposes were developed. By 1939, the need to operate at much higher radio frequencies in order to obtain narrow beams of radio energy with antennas small enough to be mounted within the nose of a fighter aircraft became urgent.

It was realised that operation at frequencies in the region of 300MHz (10cm) was required but that the microwave components, especially the high power transmitter, were not available. A systematic search for suitable techniques was put in hand under the leadership of Professor Oliphant of Birmingham University.

A superheterodyne receiver was proposed, using a commercial television TRF receiver at 45 MHz (the frequency of the pre-war British television broadcasting station in London) as the intermediate-frequency amplifier. For the mixer, it was realised that a thermionic diode would be too inefficient due to electron transit time effects. Experiments were carried out by Skinner and others into the use of various types of semiconducting crystal, with silicon having a tungsten wire contact being found to be the most efficient and robust.

The problem of providing a local oscillator was addressed by Sutton of the Royal Navy Signal School who evolved the reflex klystron (Sutton Tube) which had the great advantage relative to the alternative (a low-power split-anode magnetron) of being electrically tuneable.

For the high-power transmitter, the research team set up by Professor Oliphant developed a high-power two resonator klystron oscillator. Initially, powers of the order of 1 kW were obtained with the klystron, but the intrinsic limitations to available cathode current due to the planar cathode configuration were soon apparent. Also among Oliphant's team investigating microwave components were Professor Randall and Dr. Boot who investigated the use of a Barkhausen-Kurz positive-grid triode as a microwave detector, using a low-power magnetron as a signal source.

However, the main problem was clearly that of obtaining a microwave source of sufficient power to act as a transmitter. Randall and Boot decided to investigate the possibility of using a multi-cavity magnetron for this purpose, realising that it should be possible to make the anode in the form of a copper cylinder with a hole in its centre for the thoriated tungsten filament and having six resonant cavities machined into it, coupled to the electron flow from the filament by means of radial slots.

For the design of the cavities they considered using shorted quarter-wavelength slots and also turned to the work on ring resonators carried out by Heinrich Herz in 1886. In the event it was the Herzian resonators which they used, drilling six equally spaced holes around the filament, each of diameter equal to 0.126 times the required wavelength of approximately 10cm, coupled by slots of 0.1cm width and depth to the space surrounding the filament (*Figure 2*).

The magnetic field for the first experimental prototype magnetron was provided by a laboratory electromagnet, the open ends of the cylindrical anode of the magnetron being sealed off by copper discs bonded to the anode by means of sealing wax.

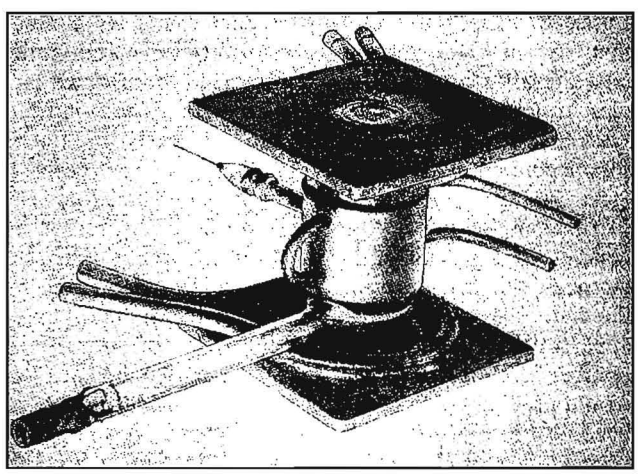

Fig. 2: This cavity magnetron of Randall and Boot first produced power on 21st February 1940. (University of Birmingham)

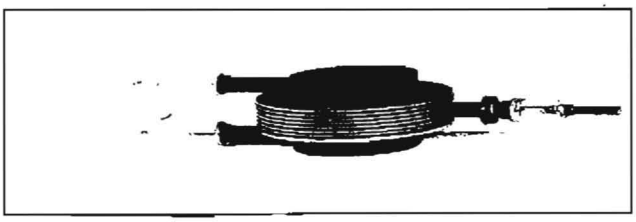

Figure 3: The E1189 cavity magnetron manufactured by GEC and first used at Worth Matravers, July 1940.

When filament power and a suitably high dc voltage was applied to the magnetron, it was immediately apparent, using automobile filament light bulbs as detectors, that a high RF power was being generated - the bulbs quickly burnt out (the power was measured as being approximately 400W). At first Randall and Boot were concerned that the frequency of the power being produced might be much lower than the intended 3000MHz frequency but, by means of standing waves on a Lecher transmission line, they were able to confirm that the waves were at a wavelength of 9cm.

The Randall and Boot prototype magnetron was quickly engineered by the British General Electric Company (GEC) into the E1189 design, early examples of which had six cavities, later examples from serial number 12 having eight cavities, and which also included the high-emission oxide cathode due to the French engineer, Henry Gutton (see *Figure 3*).

At first some instability in the frequency generated was encouraged ('mode hopping'), but this was overcome by the introduction by Sayers, also of Birmingham University, of strapping together of alternate cavities.

At this time (1941), a British Mission led by Sir Henry Tizard visited the United States of America in the hope that the very large American industry would manufacture military equipment for Britain. Among the items taken by this mission to the USA was a prototype eight-cavity 10cm magnetron type E1189, variants of which were subsequently mass produced by US companies, especially Raytheon.

In Britain, the decision was taken to discontinue the development of the klystron 10cm high-power transmitter in favour of the magnetron, although some 25kW of peak power had been obtained eventually by EMI with their klystron, it being realised that the cavity magnetron had the potential to be developed to produce very much larger peak powers than the klystron, over 1MW being obtained later in the war.

Also developed in Britain at that time was a transmit-receive microwave switch to enable one antenna to be used for both transmission and reception, the key factor being the design of the 'Soft Sutton Tube' T/R cell. The resulting 10cm microwave technology was quickly applied to Air Interception (AI) radar, to naval shipboard radar and to anti-aircraft gun laying radar.

An especially important application of microwave radar was Air-to-Surface Vessel (ASV) radar which enabled the conning towers of German U-boat submarines to be detected and the U-boat attacked in darkness, having a profound effect upon the naval war in the Atlantic.

The development of the "H2S" Blind Bombing Radar fitted to RAF heavy bombers, greatly improved bombing accuracy, especially at long range. Also developed at that time were radar beacons which were used for the navigation of aircraft back to their operating bases, especially in bad weather.

Shortly after the development of radars operating at 10cm wavelengths, radars were produced at 3cm (X-Band) and at 1.25cm (Ku-Band) in order to improve radar definition by reducing antenna bandwidths. In fact, radars at 1.25cm proved to be unsuitable in Europe due to high microwave signal absorption by atmospheric moisture.

Towards the end of WWII, the British Royal Navy developed a 3cm (X-Band) shipboard Marine Navigation Radar, the design of which was made available to the international commercial marine community at the International Meeting on Radio Aids to Marine Navigation (IMRAMN) held in London in 1946.

Among the British companies which developed commercial marine navigation radars based upon this Royal Navy design was Cossor Electronics in whose marine radar development laboratory the author, as a young design engineer, was employed in the late 1940s and subsequently becoming the company's Technical director. Cossor was acquired by Raytheon in 1961.

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